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General model of solar water heating system integration in residential building refurbishment—Potential energy savings and environmental impact

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ABSTRACT

The building sector, which accounts for about 40% of total energy consumption in Europe, offers various possibilities for achieving higher energy efficiency by introducing distributed RES. As 20% of total energy consumption in this sector is used for water heating, it follows that 8% of total energy in Europe is consumed for water heating purposes, which provides great opportunities for energy savings. Solar water heating systems (SWHSs) are a suitable technology for renewable energy source (RES) exploitation to be applied in residential building refurbishment that generate both fossil fuel savings and reductions in CO_2 emissions. Due to its complexity, SWHS integration requires a comprehensive approach including consideration of the functional and aesthetic, energy performance, and economic and ecological aspects from conceptual design through to design realization. This article defines a general model of SWHS integration in residential building refurbishment. The model is divided into several basic phases in order to facilitate problem-solving and to enable the individual optimization processes for variant design. The phases are systematically analyzed and a proper procedure and/or methods are established to solve them. At the very beginning of the suggested problem-solving procedure, the measures 'Building Potential', $\tilde{P}_B$, and 'Degree of Feasibility', p_B, are first introduced in order to estimate the suitability of SWHS integration. A Multi-Criteria compromise ranking method, is recommended for a comprehensive evaluation of design variants and for the selection of the optimal SWHS integration Design Variant. The proposed general model is also applied for solving a real problem – namely, the integration of SWHS through the refurbishment of residential buildings in the suburb of "Konjarnik" in Belgrade, Serbia, which is one of the many that were built in Belgrade after the Second World War.

Contents

Abbreviations: SWHS, solar water heating system; RES, renewable energy source; LCC, life cycle cost; BPS, building performance simulation; LCA, life cycle assessment; DM, Decision Maker; SPS, simple payback period; STC, Solar thermal collector; GFP STC, flat plate-glazed solar thermal collector; UGFP STC, flat plate-unglazed solar thermal collector; VT STC, vacuum tube solar thermal collector; BBRKL, rooms: boiler room, bathrooms, restaurant and kitchen, laundry and other rooms requiring hot water.

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1. Introduction

Fossil fuel savings, reductions in CO_2 emissions, as well as a permanent fall in SWHS prices are all important incentives for SWHS application. SWHSs are widely recognized as one of the most important types of technologies for RES exploitation in a built environment and for achieving sustainable development. The building sector, which accounts for ca. 40% of total energy consumption in Europe provides great opportunities for energy savings [1]. Exceptionally successful results can be achieved through SWHS application in residential buildings with existing central water heating systems and high user concentrations, such as multi-family residential buildings, dormitories and nursing homes.

The integrative design approach in energy efficiency optimization and sustainable building design enables the achievement of cost-effective SWHS integration. This reduces life cycle costs (LCC) and enhances buildings' comfort and inhabitability. Building performance simulation (BPS) designed for building refurbishment should encompass the following domains: the building's intrinsic performance, occupant comfort and life cycle assessment (LCA) [2–5].

This article proposes a general model of SWHS integration in residential building refurbishment, taking into account all the conflicting requirements to be satisfied: functional and aesthetic, energy performance, economic and ecological conflicting classes of requirement. An iterative procedure is adopted for the problem-solving process due to the great complexity of the problem [6]. The model is divided into several basic phases in order to facilitate problem-solving, as well as to enable individual optimization processes for designing variants. The design constraints and/or requirements cited by the Investor (Decision-Maker) are considered as high-priority requirements and are embodied in the model

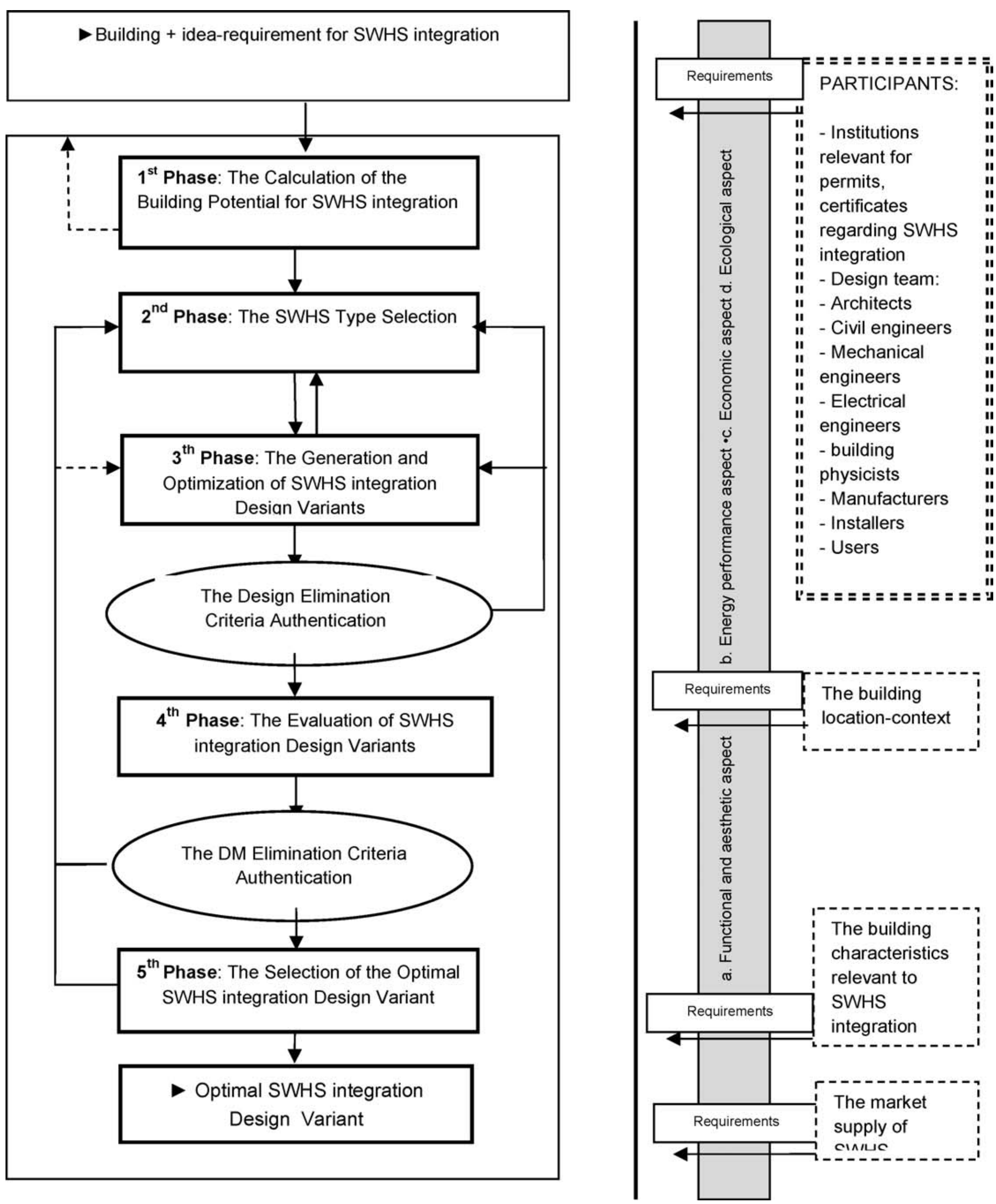


Fig. 1. The general model of SWHS integration in residential building refurbishment.

Table 1
Set of criteria and evaluation system for Building Potential calculation of SWHS integration in residential building refurbishment.

Criteria groups	Criteria functions f_i	Evaluation system – criteria evaluation values		
		min	Medium	max
A. Climatic and urban planning criteria	1. Global solar irradiance on building location (kWh/m^2)[a]	Low – Gh < 1200 kWh/m^2 −3	Medium – $1200 \leq$ Gh ≥ 1 500 kWh/m^2 0	High – Gh > 1500 kwh/m^2 3
	2. Number of favorably (south, south-west or south-east) oriented roof sides	Unfavorable – no roof sides with favorable orientations −3	Moderately favorable – 1 roof side has favorable orientation 0	Favorable-at least 2 roof sides have favorable orientations 3
	3. The number of favorably (south, south-west or south-east) oriented facade walls	Unfavorable – no facade wall has favorable orientation −3	Moderately favorable – 1 facade wall has favorable orientation 0	Favorable – at least 2 facade walls have favorable orientations 3
	4. Shading effect on roof caused by context elements (other buildings, trees, etc.)	Unfavorable – more than 50% of favorable oriented roof side surfaces are shaded −3	Moderately favorable – less than 50% of favorable oriented roof side surfaces are shaded 0	Favorable – the favorably oriented roof sides are without or almost without shading 3
	5. Shading effect on facade walls caused by context elements (other buildings, trees, etc.)	Unfavorable – all favorably oriented facade walls are shaded −3	Moderately favorable – favorably oriented façade walls are less than 50% shaded 0	Favorable – favorably oriented façade walls are without or almost without shading effects 3
B. Capacity of residential building	6. Size of residential buildings	Small size (single-unit house, duplex house) 0	Medium size (residential buildings consisting of up to 30 residential units) 1	Large size (residential buildings consisting of more than 30 residential units) 2
	7. Average daily hot water consumption per occupant (liters/occupant/day)	<40 l/occupant/day 0	40–120 l/occupant/day 1	>120 l/occupant/day 2
	8. Regular utilization of building during summer time	Irregular utilization 0	Partially regular utilization 1	Regular utilization 2
	9. Fuel type used for existing water heating system	Water heating system on natural gas 0	Water heating system on liquid oil 1	Water heating system on electrical energy 2
	10. Type of existing water heating system	Individual water heating system 0		Centralized water heating system 2
	11. State of existing water heating system	Good 0	Medium 1	Bad 2
	12. Type of existing space heating system	Centralized system – city heating station 0		Separate system – liquid oil based system 1
C. Architectural criteria relevant for SWHS integration	13. Spatial and architectural organization of residential building (layout and distances of existing BBRKL rooms-boiler room, bathrooms, restaurant and kitchen, laundry and other rooms requiring hot water)	Unfavorable – long distances between existing BBRKL rooms 0	Moderately favorable – no particularly long distances between BBRKL 1	Favorable – small distances between BBRKL rooms 2
	14. STC applicability on roof surfaces, C_R-ratio between daily hot water consumption and favorable roof surfaces for STC integration (l/m^2)	Unfavorable – $C_R \leq 30$ l/m^2 0	Moderately favorable – 30 l/m$^2 \leq C_R \leq 70$ l/m^2 1	Favorable – $C_R \geq 70$ l/m^2 2
	15. STC applicability on facade wall surfaces, C_F-ratio between daily hot water consumption and favorable area of facade walls for STC integration (l/m^2)	Unfavorable – $C_F \leq 30$ l/m^2 0	Moderately favorable – 30 l/m$^2 \leq C_R \leq 70$ l/m^2 1	Favorable – $C_R \geq 70$ l/m^2 2
	16. Ease of STC mounting on roofs and facade wall construction	Unfavorable – pitched roof slopes do not closely match planned STC tilted angles 0	Moderately favorable – only specially designed solutions can be integrated 1	Favorable – flat roofs, pitched roof slopes closely match planned STC tilted angles 2

Table 1 (*Continued*)

Criteria groups	Criteria functions f_i	Evaluation system – criteria evaluation values		
		min	Medium	max
	17. Ease of STS mounting on facade walls	Unfavorable – facade walls have special finishing, or special architectural style not suitable for STC integration	Moderately favorable – only specially designed solutions can be integrated	Favorable – no constraints; building finishing, architectural style, etc., give no limits for STC integration
		0	1	2
	Values of Building potential, $\tilde{P}_B$	−15 (min Building Potential in case of 'crisp', un-fuzzy modeling)		+38 (max Building Potential in case of 'crisp', un-fuzzy modeling)

[a] The given values are defined on the basis of Global irradiation (Gh) in Europe.

by introducing Design and Decision-Maker Elimination Criteria. For final selection of the optimal design variant, the Multi-Criteria compromise ranking method, Vikor [7,8], is recommended due to its great flexibility in modeling Decision-Maker's preference structure of criteria weights, as well as its sensitivity analysis in terms of variant 'optimality'. All phases of the model are discussed in detail and are presented in the following sections.

2. Defining a general model of SWHS integration in residential building refurbishment

The graphic representation of the proposed general model of SWHS integration in residential building refurbishment is given in Fig. 1. As it can bee seen, SWHS integration is an iterative process due to its complexity. It is divided into five basic phases: 1st phase – calculation of Building Potential for SWHS integration, 2nd phase – SWHS Type Selection, 3rd phase – generation and optimization of SWHS integration Design Variants, 4th phase – evaluation of SWHS integration Design Variants and 5th phase – selection of the optimal SWHS integration Design Variant. Design and Decision Makers Elimination criteria defined by the Designer and/or by the Decision-Makers (DM) in this model are high-priority objectives that have to be satisfied. These can be particular requirements for energy performance, functional and aesthetic, economic or ecological requirements, such as: limitations of the maximum total price for SWHS integration, limitations regarding the maximum simple payback period (SPS) and requirements regarding energy production.

2.1. Calculation of Building Potential – 1st phase

The first phase of SWHS integration problem-solving assesses the possibility of SWHS integration in the analyzed building. In line with that, 'Building Potential' is established as a measure to assess the building's feasibility for SWHS integration. 'Building Potential' is defined by an appropriate set of criteria, based on which the evaluation of particular building characteristics relevant to SWHS integration is derived. The description and evaluation system of these criteria are given in Table 1.

Since the criteria function values are usually defined by linguistic variables or qualitative grades (favorable, moderately favorable and unfavorable), besides using traditional set theory, the fuzzy set theory is also recommended for modeling them. Use of L-R fuzzy numbers comes particularly recommended, i.e., $\tilde{B} = (b, \alpha, \beta)_{LR}$, where b is the average value, and α and β are the left and right spreads, respectively. Depending on the certainty level of the grades, which are given by the experts, trapezoid or triangle fuzzy numbers could be used as well. An example of modeling the aforementioned linguistic variables – favorable, moderately favorable and unfavorable – using triangle fuzzy numbers $\tilde{B}^1$, $\tilde{B}^2$ and $\tilde{B}^3$, respectively, is shown in Fig. 2. The modeling type using triangle fuzzy numbers is suitable in cases of higher certainty of the

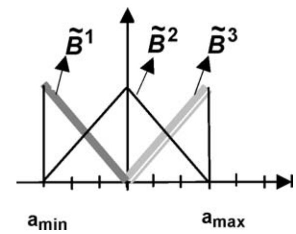


Fig. 2. Chart of linguistic variable representation by triangle fuzzy numbers.

grades given by the experts. In cases of higher uncertainity, use of trapezoid fuzzy numbers is suggested.

The measure 'Building Potential' $\tilde{P}_B$, is calculated as follows:

$$\tilde{P}_B = \sum_{i=1}^{n} \tilde{B}_i^j, \quad i = 1, 2, \ldots, n, \quad j = 1, 2, \ldots, J, \tag{1}$$

where $\tilde{B}_i^j$ is an L-R fuzzy number (grade) j for the i-th criterion function, n is the total number of criteria functions, and J is the total number of fuzzy grades. Note, the addition of fuzzy numbers is calculated by their parametric representation, (b_i, α_i, β_i) [9], where $\tilde{P}_B$, is also an L-R fuzzy number.

The measure 'Degree of Feasibility', p_B, to which the building is suitable for SWHS integration is defined as the degree to which the calculated 'Building Potential', $\tilde{P}_B$, is equal to the 'Limit value of favorable Building Potential', $\tilde{P}_G$, i.e.,

$$p_B = \mu_{\tilde{P}_B}(d_D) = d(\tilde{P}_B \cap \tilde{P}_G) = hgt\,(\tilde{P}_B \cap \tilde{P}_G) \tag{2}$$

where $\tilde{P}_G = (p_G, \alpha_G, \beta_G)$ is also an L-R fuzzy number with favorable values of Building Potential for SWHS integration, and *hgt* is the maximum height of the fuzzy numbers $\tilde{P}_B$ and $\tilde{P}_G$ intersection ordinate, Fig. 3. Observe, $0 \le p_B \le 1$ and the greater p_B is than p_{min} the higher the suitability level of the building for SWHS integration, Fig. 3. The values $0 < p_{min} \le 1$and $\tilde{P}_G$ are defined separately for each building type depending on the Decision-Maker (the Investor) goals. For multi-family residential buildings, the values of $\tilde{P}_G$ and p_{min} are suggested and shown in Fig. 3. Note, it is possible to perform a more calibrated evaluation of 'Building Potential', $\tilde{P}_B$, by introducing a greater number of linguistic grades, i.e., j = 1,2, ..., J, $J > 3$.

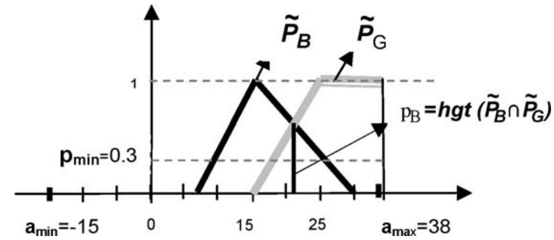


Fig. 3. Chart of Limit value of favorable Building Potential for multi-storey residential buildings.

Table 2
Criteria categories—aspects, criteria function groups and individual criteria functions for evaluation of SWHS integration Design Variants.

Aspects	Criteria function groups	Individual criteria functions
Functional and aesthetic aspect		
Class of criteria for Building Aesthetics	Compatibility of physical characteristics of STCs in relation to building envelope	Compatibility of dimensions of STCs in relation to building envelope
	Compatibility of material appearance of STCs in relation to building envelope	Compatibility of color of STCs in relation to building envelope
		Compatibility of surface characteristics (texture, fracture, surface relief, warmth to touch) of STCs in relation to building envelope
		Compatibility of glossiness–reflection of STCs in relation to building envelope
		Compatibility of transparency level in relation to building envelope[a]
	Compatibility of physical and aesthetic characteristics of STC sealing-joints in relation to building envelope	Compatibility of physical and aesthetic characteristics of STC sealing-joints in relation to building envelope
	STCs' fitting in building envelope	Naturalness of STC integration
		Relationship between composition of STC colors and materials and colors and materials on building envelope
		Design harmony
		STCs' fitting in building context
		Design innovation
	Success of visualization concept of STC integration	Success of visualization concept of STC integration simultaneously in relation to building and in relation to building context
Class of criteria for Building physics	Physical–mechanical characteristics	Mechanical characteristics of STCs (material strength, friction resistance, resistance to force impact)
		Behavior in relation to liquids (water absorption, capillary absorption, moistening/non-moistening, permeability of water, frost resistance
		Behavior in relation to air–steam of STCs
		STC characteristics in relation to deformations and destruction (behavior in relation to wind, fire, earthquake; deformations caused by changing of moisture level, temperature change, dynamic loads)
		Thermal characteristics of STCs (size modifications caused by temperature change, thermal capacity of materials, thermal resistance, thermal insulation in winter and summer)
		Acoustic characteristics of STCs
Class of criteria for Mounting	Ease of STC mounting and joint quality	Ease of mounting
		Joint quality (construction stability aspect, building physics aspect, maintenance aspect)
Energy performance aspect		Energy production on annual basis/total system costs (kWh/Euro)
		Energy production on annual basis/STCs area (kWh/m^2)
		Hot water energy demands satisfaction on annual basis (%)
		Number of months with surplus of thermal energy produced (number of months: 1-12)
Economic aspect		Total system costs (STCs + installation + other) (Euro)
		Operation and maintenance costs (Euro)
		Simple payback period (SPP) (number of years)
		Contribution of non-financial benefits (socio-economic, architectural, ecological contribution)
Ecological aspect		CO_2 reductions on annual basis due to SWHS utilization (kg)

[a] Refers only to glazed STCs.

In cases of deterministic, un-fuzzy modeling, 'Building Potential', P_B, is calculated in an analogical way, i.e., as the sum of the 'un-fuzzy' values of the defined criteria functions, Table 1. The measure 'Degree of Feasibility', p_B, is then calculated as the ratio between 'Building Potential', P_B, and maximum Building Potential P_{max}, where P_{max} is calculated as the sum of all maximum values of the defined criteria functions. An example of crisp, un-fuzzy modeling of criteria function values is also given in Table 1.

2.2. SWHS Type Selection – 2nd phase

After calculation of Building Potential, $\tilde{P}_B$, a decision on SWHS integration on the analyzed building is taken by the Decision-Maker. Next phase-SWHS Type Selection follows in the event of a positive decision.

This phase is presented graphically in Fig. 4, together with all factors affecting the process of SWHS Type Selection. The process in the second phase starts with STC Technology Type Selection

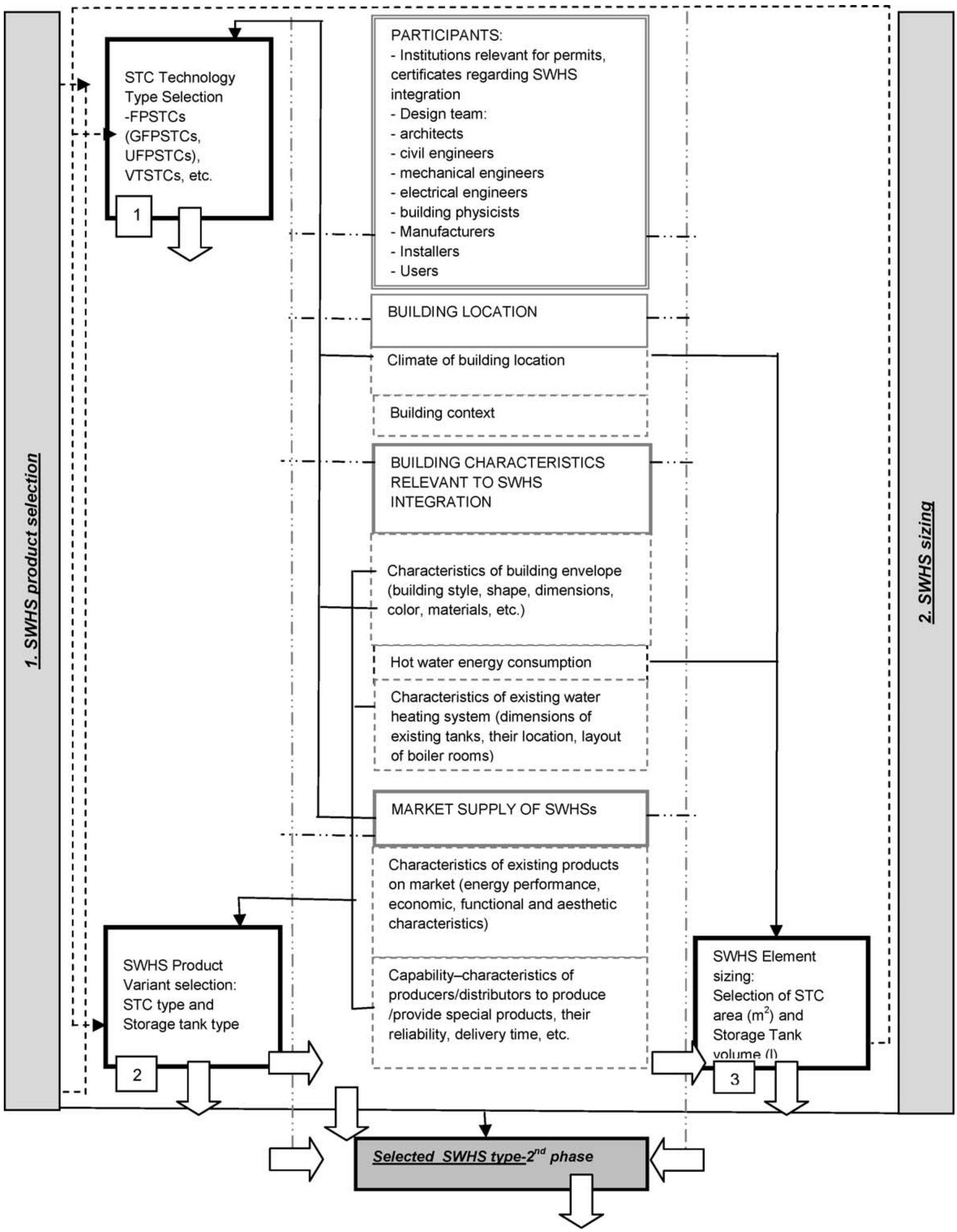


Fig. 4. Solar water heating system Type Selection.

(Fig. 4, block 1), which is based on the climate of the building's location (solar radiation), the construction and finishing design of the building envelope, as well as the availability and versatility of SWHS technology types on the market. The most common types on the market are as follows: flat plate-glazed or unglazed (GFP STCs, UGFP STCs) and vacuum tube (VT STCs) technology types. The designer makes this choice according to personal preference and creativity, taking into account the Elimination criteria and all the factors quoted in Fig. 2. In the following phases of SWHS integration (Fig. 1, phase 3 and 4), the decision is considered and calculated integrally in relation to all relevant criteria, Table 2, whereupon this phase can be repeated and the decision changed, Fig. 1.

After selection of STC Technology Type, the process continues with SWHS product variant selection (Fig. 4, block 2). It should be pointed out that, depending on the manufacturer, there is a whole spectrum of different product variants in terms of aesthetic characteristics (dimensions, shape, material type, color, surface texture, luster, light transmission), type of mounting, quality, price, etc. Generally, a particular product variant is selected on the basis of designer creativity and personal preference, keeping in mind all the quoted factors given in Fig. 2 [10].

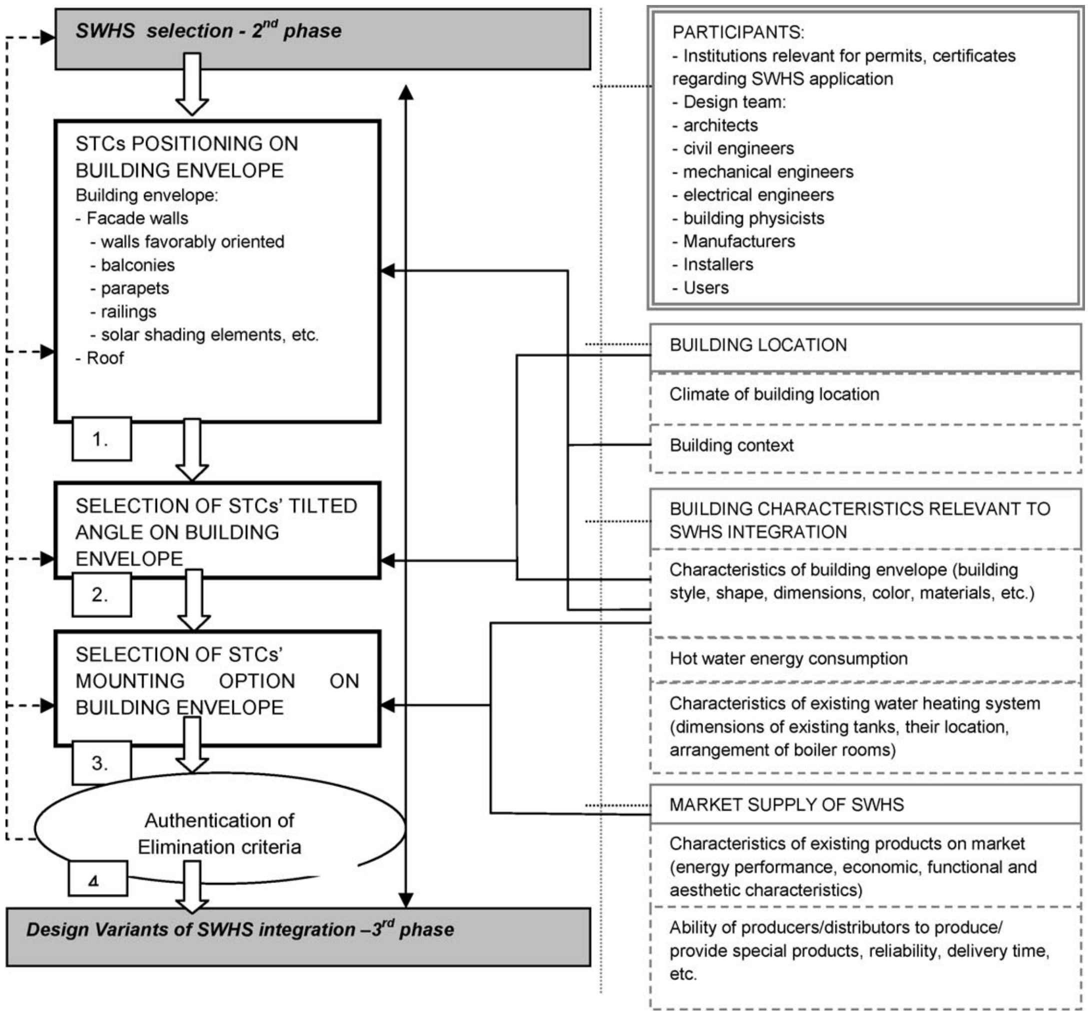


Fig. 5. Generation and optimization of SWHS integration Design Variants.

It may be observed that in some cases the process may flow in the opposite direction – i.e., the process can start from particular product variants, before the possibilities for their integration in the building are considered. The same applies in cases when the investor has a particular preference regarding manufacturer, price, product aesthetics, etc.

The last step in this phase is SWHS sizing, in which STC area (m^2) and Storage Tank volume (l) are defined by taking into account all relevant data for the climate of the building location, hot water consumption, certain characteristics of the selected SWHS and, if necessary, the Elimination criteria. Computer programs specially created for this purpose [11], greatly simplify the optimization process regarding STC and Storage Tank dimensioning. Note, the second and third phase in the proposed general model are interactive and, generally, the selected STC type and their estimated area constitute a compromise solution between the dimensioning principles and the relevant criteria for SWHS integration (functional and aesthetic, energy performance, economic and ecological criteria categories).

2.3. Generation and optimization of SWHS integration Design Variants – 3rd phase

In order to generate SWHS design variants for the building, the estimated area (m^2) of the STCs should first be positioned on the building envelope (Fig. 5, block 1). Note, the efficiency of the SWHS depends significantly on the shading effect of the building context and orientations of the facade wall(s) and roof(s) where the STCs are to be integrated. Improved SWHS energy performance can be achieved with southerly, south-westerly and south-easterly orientations, without or almost without shading effect. Consistently, the roofs are often more favorable for STCs in a city environment due to small reciprocal distances between buildings and trees which create shading effects on facade walls. The diverse variant solutions for positioning the STCs will be determined together with the factors quoted in the diagram, Fig. 5, and the designer's creativity. Usually, they are located creating balconies, parapets, railings, solar shading fittings, as well as new cladding fixtures mounted over existing facades, or even as solar panels mounted over existing roofs [12].

The next step in this phase is the selection of the STCs' tilt angle on the building envelope (Fig. 5, block 2). This angle has a direct influence on SWHS efficiency and, therefore, should be selected carefully, taking into account the proposed optimal tilt angle corresponding to the location of the building [13,14], as well as the building's functional and aesthetic characteristics. Finally, the STC mounting option should also be selected, something that has to be done carefully because of its great impact on the building's aesthetics (Fig. 5, block 3).

Once all the design variants have been created, they are compared to the Design Elimination criteria (Fig. 5, block 4) in order to verify whether they are meeting high-priority objectives. Design Elimination criteria are usually related to certain energy perfor-

mance criteria (thermal energy production, satisfying hot water energy demands, etc.). Computer programs specially created for this purpose are greatly accelerating and facilitating the optimization process regarding dimensioning of STC area, Storage Tank volume, as well as dimensioning other SWHS elements (pump, controller, heat exchanger, auxiliary heating system, etc.) [11].

Generally, it can be concluded that the total number of SWHS design variants depend on the complexity and rigidity of the requirements to be satisfied, together with the quoted characteristics of the building, Fig. 5, the technical and aesthetic characteristics of the SWHS type, the diversity of the market supply of SWHSs, as well as the designer's creativity. Observe, when a set of satisfactory design variants cannot be created within the same SWHS type, a new SWHS type is selected and the process continues in the same way as described before, Fig. 5.

2.4. Evaluation of SWHS integration Design Variants and Selection of optimal SWHS integration Design Variant – 4th and 5th phase

A Multi-Criteria compromise method, the Vikor method [7,8], enabling great flexibility in the decision-maker's preference modeling, is proposed for the evaluation of SWHS integration Design Variants and optimal design variant selection. This characteristic of the Vikor method is very important since, in practical applications, the Decision-Maker is often an entity group and its preference structure and decision-making procedure are more complex than that of individual investors. The same is true in case of individual investors without a clear preference structure. In the Vikor method [7], the preference structure is modeled directly by the weight coefficients of criteria functions, as well as by the weights of decision-making strategies. Note, using the Vikor method, the optimal variant is selected according to the value Q, Eq. (10), which represents a 'compromise' between two decision-making strategies:

- Maximum group benefit (better alternatives are good according to the majority of criteria), which is defined by the value S_j, Eq. (3) and
- Minimum of maximum deviation of ideal values (a better alternative must not be very bad according to any criteria) which is defined by the value R_j, Eq. (5).

The values S_j, R_j and Q_j are calculated as follows:

$$S_j = \sum_{i=1}^{n} w_i d_{ij}, \quad i = 1, 2, \ldots, n, \quad j = 1, 2, \ldots, m, \tag{3}$$

$$d_{ij} = \frac{f_i^* - f_{ij}}{D_i}, \quad D_i = (f_i^* - f_i^-), \quad i = 1, 2, \ldots, n, \quad j = 1, 2, \ldots, m, \tag{4}$$

$$R_j = \max_i [w_i d_{ij}], \quad i = 1, 2, \ldots, n, \quad j = 1, 2, \ldots, m, \tag{5}$$

$$QS_j = \frac{S_j - S^*}{S^- - S^*}, \quad j = 1, 2, \ldots, m, \tag{6}$$

$$S^* = \min_j S_j, \qquad S^- = \max_j S_j, \quad j = 1, 2, \ldots, m, \tag{7}$$

$$R^* = \min_j R_j, \qquad R^- = \max_j R_j, \quad j = 1, 2, \ldots, m, \tag{8}$$

$$QR_j = \frac{R_j - R^*}{R^- - R^*}, \quad j = 1, 2, \ldots m, \tag{9}$$

$$Q_j = \nu QS_j + (1 - \nu) QR_j, \quad j = 1, 2, \ldots, m, \tag{10}$$

where f_i^* and f_i^- indicate the best and worst value of all criteria functions, respectively, ω_i is the criteria weight, ν is the weight

Fig. 6. Building layout in suburb of "Konjarnik", Belgrade.

for the strategy of maximum group utility $(1 - \nu)$, is the weight of the individual regret, n is the total number of criteria and m is the alternative's total number. This method also verifies the stability of variant 'optimality' by introducing the value DQ, Eq. (12), and, in the same way, gives a more distinctive image of the 'advantage level' of the best-ranked alternative V^1 in relation to the next best-ranked alternative V^2. Alternative V^1 is best-ranked under measure Q, if the following two conditions are satisfied,

$$Q(V^1) - QV^2 \geq DQ, \tag{11}$$

$$DQ = \min\left(0.25; \quad \frac{1}{m-1}\right), \tag{12}$$

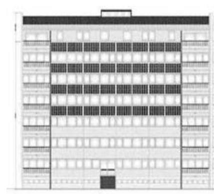
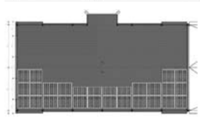
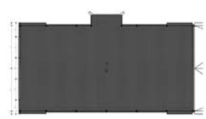
where $Q(V^1)$ and $Q(V^2)$ are the first and second ranked variants under measure Q, respectively.

The set of all criteria relevant to integral decision-making is defined, Table 2, in order to achieve a comprehensive evaluation of design variants. Given SWHS integration complexity, a hierarchical criteria structure is given. At the highest level, there are general criteria categories–aspects that are further divided into sub-categories, which are further divided into criteria groups. At the lowest level, individual criteria are used to evaluate all important characteristics of SWHS integration Design Variants. The weight coefficients are structured in a similar way to the criteria function provided that, $\sum_{i=1}^{N} w_i = 1$, $\sum_{j=1}^{J_i} w_{ij} = \alpha_i$, $\sum_{k=1}^{K_{ij}} w_{ijk} = w_{ij}$, where w_{ijk} is the weight coefficient of the individual criteria function f_k for criteria group j inside criteria category i, w_{ij} is the weight coefficient of criteria group j for criteria category i, w_i is the weight coefficient of criteria category i, K_{ij} is the total number of individual criteria functions f_k inside criteria group j of criteria category i, J_i is the total number of criteria groups inside criteria category i and N is the total number of criteria categories. Note, the values of the criteria weights directly depend on the decision-maker's preference structure and should be individually defined for each specific evaluation.

3. Application of proposed general model of SWHS integration in residential buildings in suburb of "Konjarnik" in Belgrade, Serbia

The proposed general model of SWHS integration is applied in residential buildings in the suburb of "Konjarnik", which is one of the many that were built in Belgrade after the Second World War. Due to high housing demand on the one hand and the few prefabricated systems in use on the other, these suburbs are chiefly made up of typical buildings (Fig. 6). One of them, representative of the analyzed suburb, "Konjarnik", with typical south-north orientation and a large rectangular shape is shown in Figs. 7 and 8.

Table 3
Characteristics of Design Variants of SWHS integration in existing typical buildings in suburb of "Konjarnik" in Belgrade.

	Design Variant 1	Design Variant 2	Design Variant 3	Design Variant 4
Solar thermal collector	Custom-made Doma flex Alu collectors, 100 m^2 	Custom-made Doma flex Alu collectors, 90 m^2 	Custom-made Doma flex Alu collectors, 120 m^2 	Custom-made Doma flex Alu collectors, 55 m^2 
Position	Roof South-west part of roof	Facade wall Parapets on south-west facade wall	Facade wall Parapets on south-west facade wall	Facade wall Parapets on south-west facade wall
Tilted angle	40°	90° – Vertical position	45°	0° – Horizontal position
Mounting option	Metal profiles mounted on existing walls	Metal profiles mounted on existing parapets	Metal profiles mounted on existing parapets	Metal profiles mounted on existing balconies
Design Variant appearance				
Facade				
Roof layout				
SPP < 10 years	7 Years	9 Years	8 Years	8 Years

As the buildings in the suburb of "Konjarnik" consist of lamellas, the analysis in the article focuses on one of them. On average, there are 28 flats housing about 90 occupants each. Average hot water demand per occupant is 80 l (20–50°) per day, or 251 kWh/day, or 91618.3 kWh/year for a lamella.

The established measurements for 'Building Potential', P_B, and the 'Degree of Feasibility', p_B, Table 1 and Fig. 3, are calculated using 'crisp', un-fuzzy set theory for modeling criteria values, which are $P_B = 20$, $p_B = 0.53 > p_{min} = 0.3$, respectively. According to the established measurements, the analyzed building is suitable for SWHS integration, Fig. 3.

GFP STCs are selected as the most appropriate for all design variants, due to climate conditions in Belgrade. Given their good aesthetic characteristics and the possibility for custom-made products to be delivered in a timely manner and at a reasonable price, Doma flex Alu STCs manufactured by Austrian AKS Doma were chosen. This presupposes a storage tank volume of 14,400 l, which represents double average daily hot water consumption [15]. Given

Fig. 7. Typical Building before attic annex in "Konjarnik" suburb, Belgrade.

Fig. 8. Typical building after attic annex.

Table 4
Values of criteria functions for Variants A1–A4 of SWHS integration in existing typical buildings of suburb of "Konjarnik" in Belgrade.

f_i	Criteria functions	ω_i	ext	A1	A2	A3	A4	f_i^*	f_i^-	$D_i = (f_i^* - f_i^-)$
f_1	Compatibility of STC dimensions (mm) in relation to building envelope	0.024	max	4.0	5.0	5.0	5.0	5.0	4.0	1.0
f_2	Compatibility of color of STCs in relation to building envelope	0.006	max	5.0	4.0	4.0	4.0	5.0	4.0	1.0
f_3	Compatibility of STC surface characteristics (texture, fracture, surface relief, warmth to touch) in relation to building envelope	0.006	max	5.0	4.0	4.0	4.0	5.0	4.0	1.0
f_4	Compatibility of glossiness–reflection of STCs in relation to building envelope	0.006	max	5.0	4.0	3.0	2.0	5.0	2.0	3.0
f_5	Compatibility of transparency level in relation to building envelope[a]	0.006	max	5.0	4.0	4.0	5.0	5.0	4.0	1.0
f_6	Compatibility of physical and aesthetic characteristics of sealing-joints of STCs in relation to building envelope	0.018	max	4.0	2.0	2.0	3.0	4.0	2.0	2.0
f_7	Naturalness of SCS integration	0.0085	max	5.0	4.0	3.0	3.0	5.0	3.0	2.0
f_8	Relationship between composition of colors and STC materials and colors and materials on building envelope	0.0045	max	5.0	4.0	4.0	3.0	5.0	3.0	2.0
f_9	Design harmony	0.005	max	4.0	3.0	3.0	3.0	4.0	3.0	1.0
f_{10}	STC fitting in building context	0.0065	max	4.0	3.0	2.0	1.0	4.0	1.0	3.0
f_{11}	Design innovation	0.006	max	3.0	3.0	2.0	3.0	3.0	2.0	1.0
f_{12}	Success of visualization concept of STC integration simultaneously in relation to building and in relation to closer and broader building context	0.005	max	4.0	3.0	3.0	2.0	4.0	2.0	2.0
f_{19}	Ease of mounting	0.036	max	5.0	4.0	3.0	4.0	5.0	3.0	2.0
f_{20}	Joint quality (construction stability aspect, building physics aspect, maintenance aspect)	0.054	max	5.0	5.0	4.0	5.0	5.0	4.0	1.0
f_{21}	Energy production on annual basis/total system costs (kWh/Euro)	0.075	max	0.7	0.5	0.6	0.6	0.7	0.5	0.2
f_{22}	Energy production on annual basis/STC area (kWh/m^2)	0.075	max	492.7	356.8	395.1	390.5	492.7	356.1	136.6
f_{23}	Hot water energy demands satisfaction on annual basis (%)	0.075	max	53.6	35	51.7	23.4	53.6	23.4	30.2
f_{25}	Total system costs (STCs + installation + other) (Euro)	0.09	min	70000	63000	84000	38500	38500	84000	-45500
f_{27}	Simple payback period (SPP) (number of years)	0.12	min	7	9	8	8	7	9	-2
f_{28}	Importance–contribution of non-financial benefits (socio-economic, architectural, ecological importance – contribution)	0.03	max	4.0	4.0	4.0	4.0	4.0	4.0	0.0
f_{29}	CO_2 reductions on annual basis due to SWHS utilization (kg)	0.1	max	39908	26013	38402	17395	39908	17395	22513

f_{21}–f_{24} are calculated on the basis of computer simulations in Polysun 4.3. f_{25} is calculated on the basis of the price of EUR 700 – total system costs per 1 m^2 of STC. f_{27} is calculated on the basis of the following assumptions: 0.81 kg/kWh of CO_2 emissions for a fuel oil-based water heating system [18], 3% inflation rate of fuel price on the world market [19], assuming a price of EUR 25 for 1 t of CO_2 on the European market [20]. The economic analysis assumes that there are no financial incentives for the project other than interest-free credit. Function f_{29} is calculated on the assumption that 0.81 kg CO_2/kWh thermal energy is reduced when a fuel oil-based water heating system is substituted by SWHS [18].

[a] This refers only to GSTCs.

the factors listed in Fig. 4, an SWHS with an electricity-powered auxiliary system (also available in the database of the Polysun 4.3 computer program) is used for this type of building.

3.1. Generation of SWHS Design Variants and optimal SWHS Design Variant selection for residential buildings in the suburb of "Konjarnik" – Belgrade

Taking into account all the relevant factors quoted in Fig. 5 (orientation, shading effects, etc.), the south-west oriented facade and south-west oriented side of the roof are selected as the most appropriate positions on the building envelope for STC integration [16]. The tilted angles of 40°, 90°, 45° and 0° are used as the most congruous in terms of functionality and aesthetics, mounting options and climatic conditions in Belgrade. On that basis, a number of variants were created and then tested using the Design Elimination criteria: *The optimal ratio between hot water production and STC area is $R_{W,A} \approx 70\ l/m^2$* [17]. Only those variants that created aesthetically harmonic glazed surfaces on the existing walls, parapets and balconies, and, at the same time, complied with the Design Elimination criteria, are deemed appropriate, Table 3. Note, for all selected Design Variants, the metal profiles provided by the manufacturer are used for STC mounting.

DM elimination criteria in this case, which were defined in agreement with officials responsible for the maintenance of existing residential buildings in the suburb of "Konjarnik" in Belgrade, were as follows: *maximum of 10 years of simple payback period (SPP) for total investment*. After evaluation of all selected alternatives regarding the established set of criteria, Table 4, the alternatives were also tested on the DM Elimination criteria. In this case, all selected alternatives met the required criteria and, therefore, were further examined.

Eqs. (3)–(10), which are used to calculate the values of $S^* = \min S_j$, $S^- = \max S_j$, $R^* = \min R_j$, $R^- = \max R_j$ ($S^* = 0.08$, $S^- = 0.42$, $R^* = 0.06$, $R^- = 0.12$) and the values of QS, QR and Q for $v = 0.5$, are presented in Tables 5 and 6. Note, $v = 0.5$ denotes equal participation of the

Table 5
Values of measures d_{ij}, S_i and R_i for Design Variants A1–A4.

Values of measures d_{ij}, S_i and R_i for Design Variants A1–A4		A1	A2	A3	A4
$w_i d_{ij}$	f_1	0.02	0.00	0.02	0.00
	f_2	0.00	0.00	0.01	0.00
	f_3	0.00	0.00	0.01	0.00
	f_4	0.00	0.00	0.01	0.01
	f_5	0.00	0.00	0.01	0.00
	f_6	−0.01	0.01	0.01	0.01
	f_7	0.00	0.00	0.01	0.01
	f_8	0.00	0.00	0.00	0.00
	f_9	0.00	0.00	0.01	0.00
	f_{10}	0.00	0.00	0.01	0.01
	f_{11}	0.00	0.00	0.00	0.00
	f_{12}	0.00	0.01	0.02	0.02
	f_{19}	0.00	0.02	0.04	0.02
	f_{20}	0.00	0.00	0.05	0.00
	f_{21}	0.00	0.08	0.04	0.04
	f_{22}	0.00	0.07	0.05	0.06
	f_{23}	0.00	0.05	0.00	0.08
	f_{25}	0.06	0.05	0.09	0.00
	f_{27}	0.00	0.12	0.06	0.06
	f_{29}	0.00	0.06	0.01	0.10
$S_j = \Sigma\ \omega_i d_{ij}$		0.08	0.49	0.45	0.42
$R_j = \max\ [\omega_i\ d_{ij}]$		0.06	0.12	0.09	0.10

Table 6
Values of measures QS, QR and Q for Design Variants A1–A4.

Values of measures QS, QR and Q for variants A1–A4	A1	A2	A3	A4
$QS_j = (S_j - S^*)/(S^- - S^*)$	−0.01	1.21	1.10	0.99
$QR_j = (R_j - R^*)/(R^- - R^*)$	0.00	1.00	0.50	0.67
$Q_j = \nu \times QS_j + (1-\nu) \times QR_j$; $\nu = 0.5$	0.00	1.10	0.80	0.83

Table 7
The values of measure DQ for Design Variants A1–A4.

"The advantages" DQ_j	A1–A3	A3–A4	A4–A2
	0.8	0.03	0.30

strategies: Maximum group benefit and min–max strategy. The rankings for the measures QS, QR and Q are: QS: A1, A4, A3, A2; QR: A1, A3, A4, A2; Q: A1, A3, A4, A.

"The advantages", DQ, of the alternatives are presented in Table 7. As the level for sufficient advantage is 0.25, Eq. (12), the alternative A1 has sufficient advantage and constitutes a compromise solution for the given set of criteria, their preference structure and strategy weights.

4. Conclusions

This article defines a general model of SWHS integration in residential building refurbishment. An iterative procedure is adopted for the problem-solving process due to great problem complexity presented by the functional and aesthetic, energy performance, economic and ecological conflicting classes of requirements. The model is divided into several basic phases in order to facilitate problem-solving and to enable the individual optimization processes for variant design. The phases are systematically analyzed and a proper procedure and/or methods are established to solve them. At the very beginning of the suggested problem-solving procedure, the measures 'Building Potential', $\tilde{P}_B$, and 'Degree of Feasibility', p_B, are first introduced in order to estimate the suitability of SWHS integration. 'Building Potential', $\tilde{P}_B$, is defined by the set of criteria functions, on the basis of which the particular building characteristics relevant to SWHS integration are evaluated in a comprehensive way.

The 'Degree of Feasibility', p_B, is established as the measure where the calculated Building Potential $\tilde{P}_B$ is equal to the 'Limit value of favorable Building Potential', $\tilde{P}_G$, for SWHS integration. Besides using traditional 'crisp' theory, the application of 'fuzzy' set theory for modeling is also proposed, given that the values of the established criteria functions are linguistic variables. In particular, the usage of L-R fuzzy numbers is recommended. A decision on SWHS integration in the building is taken by the Decision-Maker (i.e., Investor) on the basis of the value p_B.

The constraints and requirements given by the Decision-Maker and/or Designer in the proposed model are represented by the Elimination criteria and are considered as high-priority objectives to be satisfied during the process of generating and optimizing design variants. Note, the Elimination criteria can be referred to as landmarks in terms of the iterative procedure established in this problem-solving process.

A Multi-Criteria Decision Making method, Vikor [7], enabling great flexibility in modeling the Decision-Maker's preference structure of criteria weights, is recommended for a comprehensive and precise evaluation of design variants. This method begins by defining a relevant set of criteria functions with a hierarchical structure in order to enable accurate and integral assessment of design variants. The 'optimal' design variant is selected using the measure Q that comprises both: maximum group benefit and the 'min–max strategy' for the decision-making process. The stability analysis on the 'optimality' of the selected design variant is also included. In some cases, for more delicate stability analysis, the Extended Vikor method [8] is also recommended.

The proposed general model is applied for solving real problems, given that an SWHS is integrated into residential buildings in the suburb of "Konjarnik", in Belgrade. All the established procedures and methods are discussed in detail and the results are presented in Section 3.

The model gives clear and systematic guidelines that lead to the optimal design solution for SWHS integration in terms of the established set of criteria and their preference structure. Separate model segments facilitate individual optimization processes for variant design when it comes to investments costs, energy yield, aesthetic

requirements, etc.

A similar approach, presented in this article, can be applied in defining general models of SWHS integration in the refurbishment of other building types (e.g. commercial, industrial, agricultural buildings, etc.), and as a basis for defining general models of SWHS integration in new building designs.

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